Archives

The Los Alamos Research Quarterly is published to communicate the Laboratory's achievements and how they benefit our neighbors, our nation, and the world.

The Research Quarterly highlights our ongoing work to enhance global security by ensuring the safety and reliability of the U.S. nuclear weapons stockpile, developing technical solutions to reduce the threat of weapons of mass destruction, and solving problems related to energy, environment, infrastructure, health, and national security.

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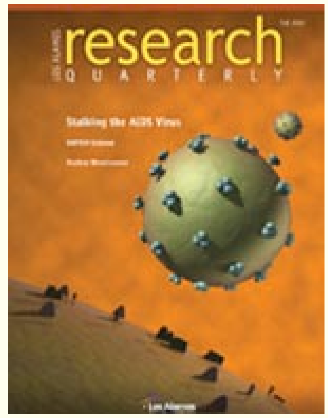

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Assessing the Global Hydrogen Budget

A recent study—published in *Nature* by Thom Rahn, a Frederick Reines Postdoctoral Fellow, and colleagues—indicates that molecular hydrogen in the atmosphere tends to enrich deuterium in the stratosphere, home to Earth's ozone layer. In this study, Rahn collaborated with researchers from the California Institute of Technology, the University of California at Berkeley, the University of California at Irvine, and the National Center for Atmospheric Research. Their finding has ramifications for the use of hydrogen fuel cells as an alternative energy source to fossil fuels.

Extremely small concentrations of deuterium are known to exist throughout the universe. However, deuterium levels in the stratosphere are nearly one and a half times higher than they are in seawater—Earth's most abundant reservoir of elemental hydrogen and hence an excellent reference point.

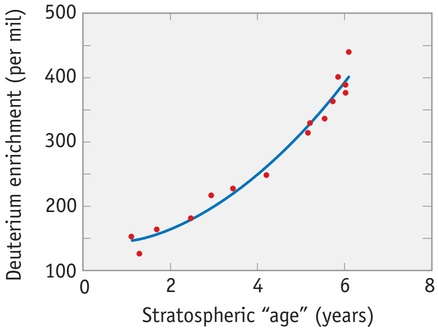
Rahn and colleagues have shown that this enrichment results from isotopic-mass-dependent reactions related to the photochemical oxidation of methane. Methane has both natural and manmade sources and is a major contributor to atmospheric molecular hydrogen. Quantifying its contribution to the global hydrogen budget is essential to assess the environmental benefits and risks of using hydrogen fuel cells on a large scale.

A hydrogen-based economy should reduce pollutants like nitrogen oxides, the precursors of urban smog, and particulates that result from the combustion of fossil fuels. Such reductions would improve urban air quality and enhance human health. However, the unavoidable escape of molecular hydrogen from the production, storage, and transfer facilities associated with a fuel-cell infrastructure would increase hydrogen concentrations in the atmosphere.

Since hydrogen produces water in the stratosphere, there is concern that its buildup could increase global warming and catalyze chemical reactions that would further deplete Earth's ozone layer near the poles. In the lower troposphere, hydrogen buildup could also reduce the abundance of hydroxyl radicals—chemicals that help scrub greenhouse gases such as methane from the atmosphere.

Developing models to study the hydrogen budget will allow scientists to address these concerns and avoid another chlorofluorocarbon blunder. "Our study gives us a tool in looking ahead at potential consequences if a hydrogen-based energy economy is not properly managed," said Rahn. "No one foresaw what CFCs would do to the stratosphere when they were being developed. But now we have a chance to be proactive in saying what we need to consider when moving to a hydrogen economy."

Building on the Laboratory's expertise in hydrogen research, Manvendra Dubey, Rahn's colleague and mentor, is collaborating with the National Oceanic and Atmospheric Administration and the National Center for Atmospheric Research in applying models to study the effects of potential leakage during hydrogen production and transport.



Deuterium levels in stratospheric hydrogen (relative to seawater) versus mean age of air samples.

Dubey stressed, "It is extremely important to establish a global baseline of hydrogen and its budget in order to understand any changes in the future." Baseline measurements have proved critical to understanding global increases of carbon dioxide levels. Carbon dioxide measurements dating from the mid-1950s have shown an accelerating increase in the greenhouse gases produced from burning fossil fuels. "If we didn't have a carbon dioxide baseline, we would still be arguing whether the increase was due to human factors," Dubey said. Developing a hydrogen baseline will help the Department of Energy assess the varied options for guaranteeing the nation's energy security while managing the risks of global climate change.

—*James E. Rickman*

Mesa View

Richard Robinson

William H. Press,
Deputy Director for Science and Technology

National Labs and Universities: Proven Synergy

Institutions that resemble national laboratories actually come in two flavors: Some, like the Naval Research Laboratory or NASA's Goddard Space Flight Center, are directly managed by the Federal government. Others, like Los Alamos and Lawrence Livermore National Laboratories, operated for the Department of Energy and the National Nuclear Security Administration, or the Department of Defense's Lincoln Laboratory, are managed on behalf of the Federal government by non-Federal entities—predominantly by universities. These latter labs are called FFRDCs, Federally Funded Research and Development Centers. Los Alamos is in fact an FFRDC.

In 2000 (the latest available figures), about \$265 billion was spent on R&D activities in the United States. This total divides into about \$85 billion funded for public purposes (i.e., by government, nonprofits, and universities) and \$180 billion funded by the private sector (i.e., by industry). Defense-related R&D here counts as public, even if it is performed by industry.

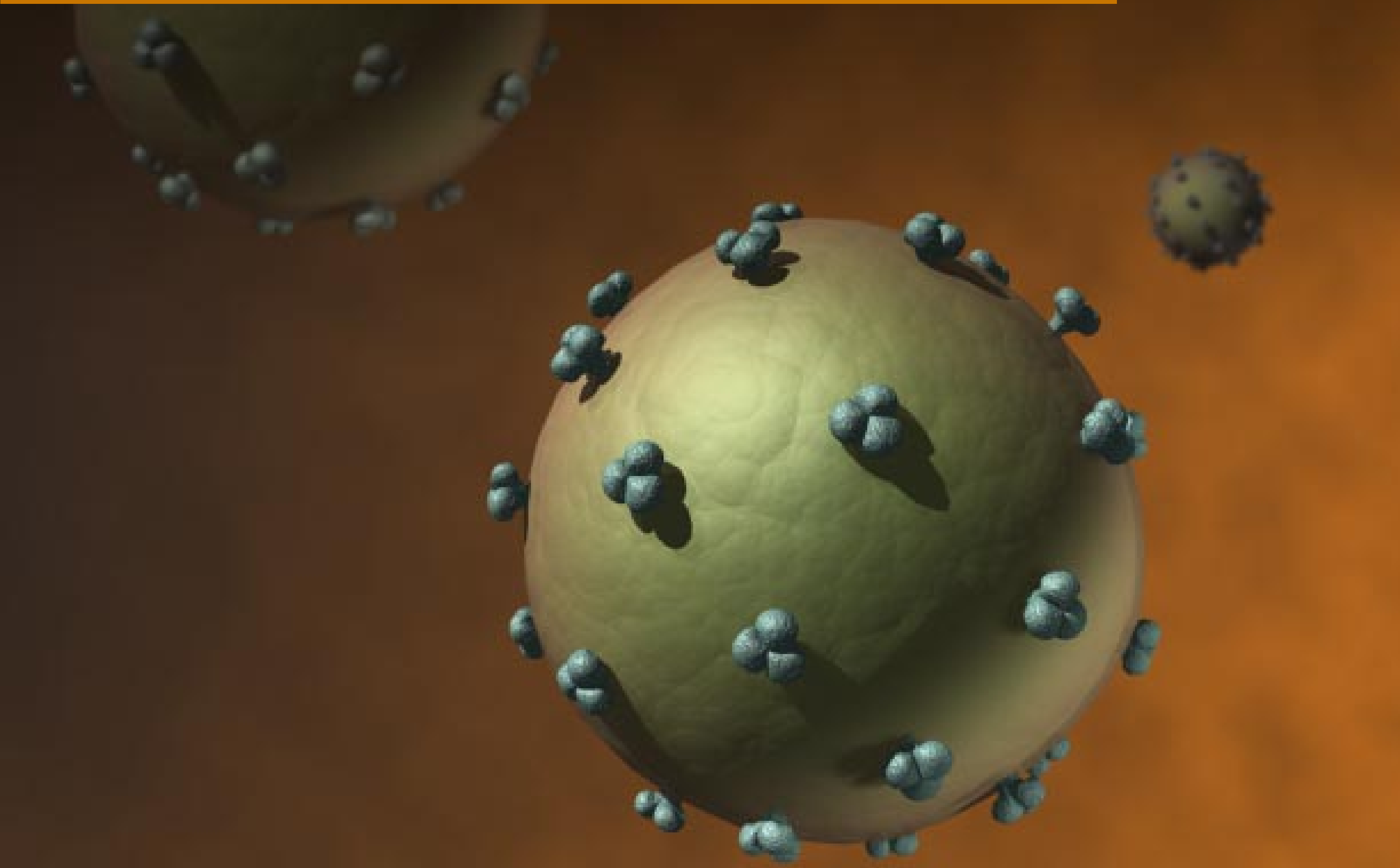
We can break down the \$85 billion of public R&D according to the kind of institution doing the work: \$30 billion to universities plus \$5 billion to other nonprofits, \$20 billion to industry, \$20 billion executed within the Federal government (including the directly managed laboratories), and \$10 billion to FFRDCs.

Universities deserve, and get, the largest share of public R&D, because they are the primary engine of science and technology creativity in our country. The world is envious of our system of great research universities and the diversity of talent that they house. But, historically and now, our nation turns to its FFRDCs when it needs the sharpest-possible cutting edge on mission-related R&D, both for directed research and for vital parts of the underlying basic science.

It is no coincidence that most of the \$10 billion for FFRDCs goes to ones that are managed by research universities or that the largest part of this funding goes to the University of California's laboratories, including Los Alamos. In creating this direct interface between its greatest universities and its greatest national laboratories, our nation found a synergy that multiplies the effectiveness of both kinds of institutions in solving its most important national problems.

In 2005, the contract to manage Los Alamos will be competed for the first time in sixty years. Understandably, few of us here on the mesa favored the decision to compete. For some, there is a tendency to assume the worst, that the competition outcome will be determined by low politics, not high principles.

I don't accept this negativism. I know from personal interaction that DOE's and NNSA's top leaders understand and value what is unique about Los Alamos and that they understand the critical role played by a great university's management. Personally, I don't think they will find any university better than the University of California at filling this essential role—not even close. Let's compete!



Stalking the AIDS Virus

A Killer with Many Faces

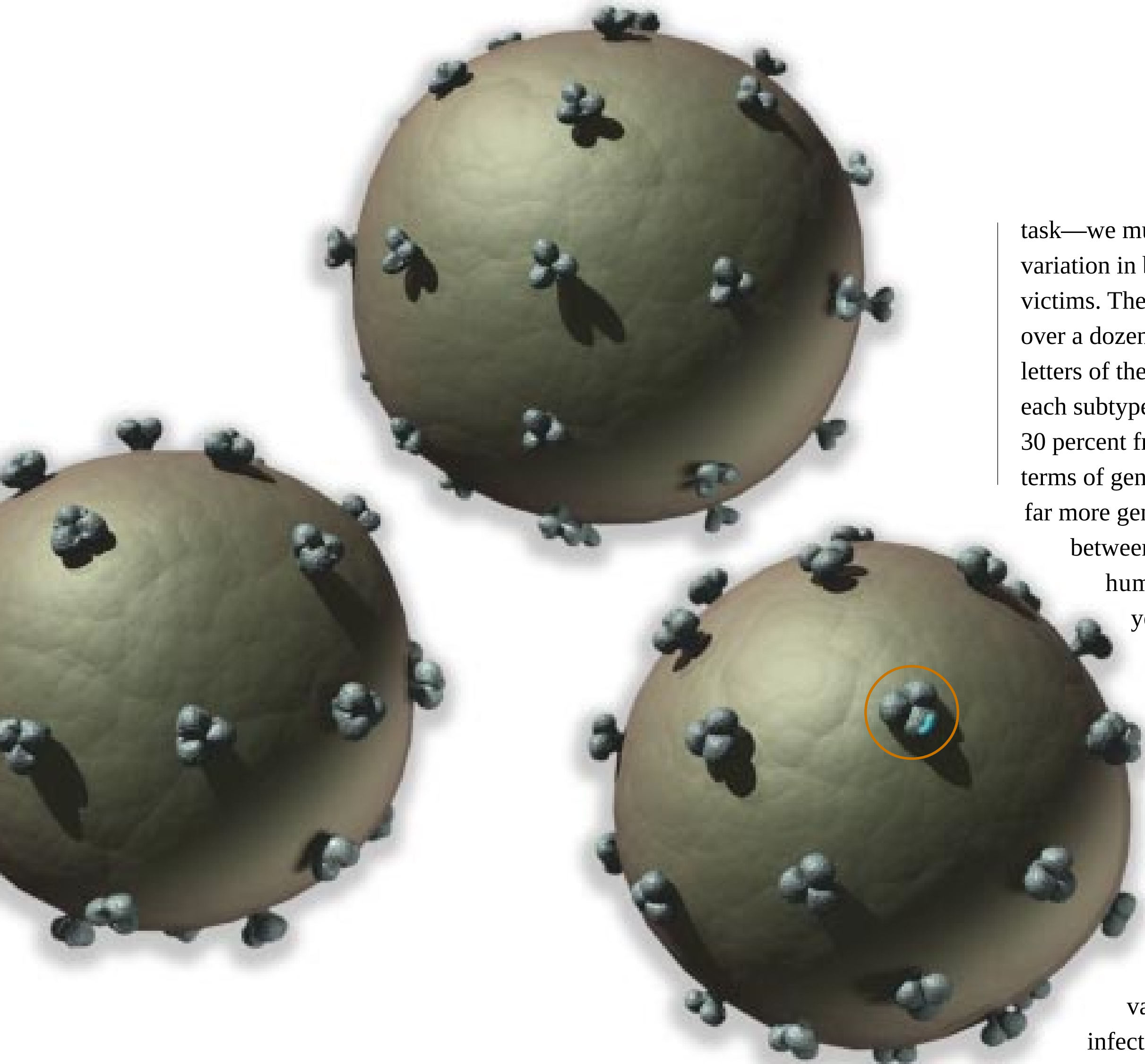
by Vin LoPresti

Developing an AIDS vaccine is "the moral obligation of our times."

Illustrations by Vicente Garcia

An improved understanding of the interaction between HIV and the immune system has brought Lab researchers closer to identifying key parameters in AIDS vaccine development.

Discussing her research with the compassionate zeal of one attuned to human suffering, biologist Bette Korber talks compellingly of her campaign against modern medicine's most formidable infectious adversary—the AIDS virus, HIV (human immunodeficiency virus): "Even if we fail, we have to try as hard as we can. We owe it to future generations. I do think it's the moral obligation of our times."



Artist's conception of three mutant forms of the AIDS virus, HIV, illustrating subtle differences in the shape of the virus' surface glycoprotein (gp120). Although similar enough in overall shape to allow all viruses to remain infectious, the surface proteins vary in their conformation (three-dimensional geometry). Similar variation is also found in the virus' internal proteins, which are not shown in this view. Each virus' outer membrane is derived from a cell that it had previously infected. As shown in the circled protein on the surface of the right-most virus, only a very small fragment of the viral protein (in blue) is ultimately recognized by cytotoxic T cells, part of the immune system's viral defense (see the illustration on page 16).

Korber is part of a growing cadre of immunology researchers who view an effective AIDS vaccine as the holy grail, and she collaborates with a diverse group of colleagues. Their recent research offers hope that important brushstrokes in the picture of HIV's interaction with the immune system are beginning to delineate a more detailed backdrop against which to intervene in the pathological drama of AIDS.

Variation in the Virus and Its Victims

To understand how HIV can so completely compromise its victims' immune systems—and why designing an effective vaccine is such a difficult task—we must appreciate the genetic variation in both the virus and its victims. The virus exists globally as over a dozen subtypes (named with letters of the alphabet), and genes in each subtypes typically differ by 25 to 30 percent from all other subtypes in terms of genetic information. This is far more genetic variation than is found between most of the genes of humans and chimpanzees; yet humans and chimps are considered separate species, while the HIV subtypes are considered parts of a single viral species. Moreover, even within the same subtype—the predominant B subtype in the United States, for example—the genetic variation between viruses infecting different individuals is typically 10 to 15 percent and steadily increasing. Such genetic variability poses an enormous challenge to both vaccine developers and to the immune system defenses of infected individuals. As a service to the AIDS research community, Korber and her Los Alamos colleagues maintain an extensive online database of the genetic sequences found in strains of these HIV subtypes (www.hiv.lanl.gov). This database is accompanied by a variety of analytical software tools and is extensively used by scientists worldwide.

For HIV victims, this viral variability is further complicated by human genetic variation. Since only identical twins have exactly the same copies (or alleles) of every human gene, the rest of us are, by definition, variant to a greater or lesser degree. With respect to HIV infection, the relevant human variation rests primarily in the information contained in the genes for the HLA proteins (human leukocyte antigen). These proteins form a collection of regulatory macromolecules on the surface of virtually all human cells. For example, HLA proteins have long been known as the culprits in instigating certain types of graft rejection. In the context of normal immune system function, they are key molecular intermediaries in the process by which the two major types of immune system T cells—T-helper cells and cytotoxic T cells—recognize invading pathogens such as bacteria and viruses (see the sidebar on this page).

The HIV-HLA Connection

We receive genes for two sets of HLA proteins, one set from each parent. Each set consists of proteins denoted as A, B, C, and D. Since each protein comes in many slightly different forms (or is polymorphic), each person's cell surfaces most commonly carry two distinct sets of HLA proteins. These protein sets partly define an individual's immunological uniqueness. For example, if we ignore D, whose biology is more complex, one person's cells might carry on their surfaces A1 and A24, B27 and B57, and C3 and C5. The numbers simply indicate structural variants of the A, B, and C proteins inherited from each parent. The cells of a second, biologically unrelated individual would likely carry a different set of HLA proteins (for example, A2 and A15, etc.).

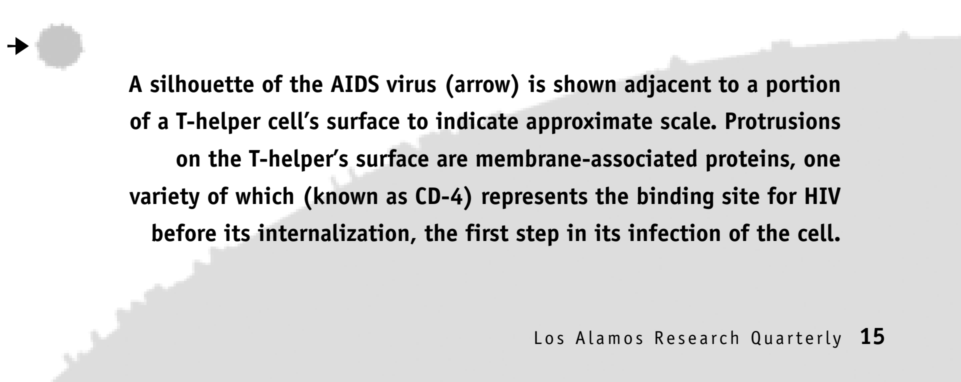
Korber and her colleagues have been studying the HLA-A, -B, and -C proteins (denoted HLA Class I) because they regulate the immune system's response to viruses, including HIV.

How HIV Cripples

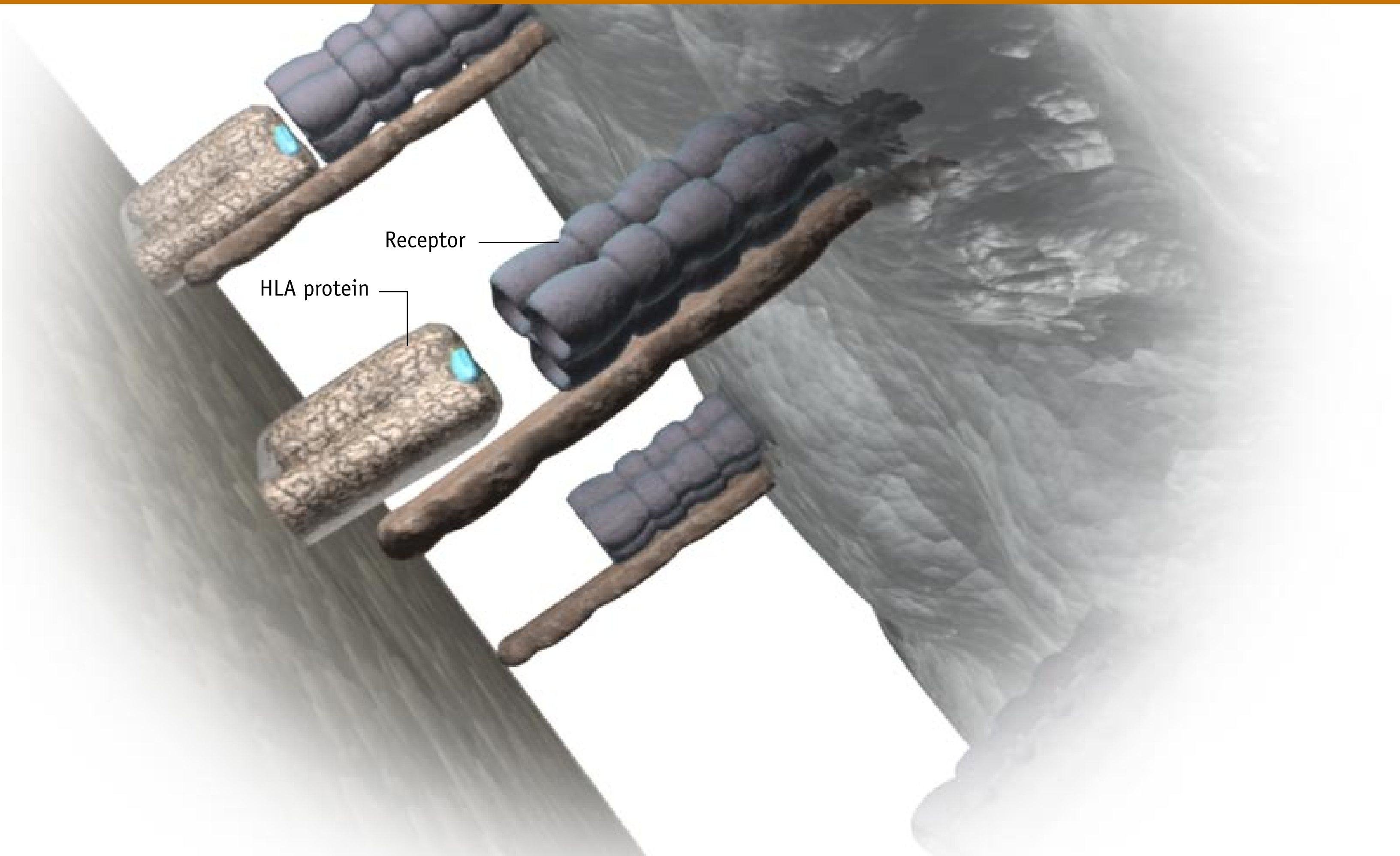
T- helper cells function as the central processing unit of the immune system. They respond to invading pathogens by releasing signals (cytokines) that regulate a broad spectrum of immunological functions, such as antibody production, inflammation, the activity of scavenger white blood cells, and even the production of new red blood cells. Because of its molecular structure, HIV can infect all T-helper cells, and infected T-helpers thus become reservoirs for replicating the virus—vehicles for its spread to millions of other T-helpers. As the virus spreads through the bloodstream, antibodies—which are effective only outside cells—can shield additional T-helpers from becoming infected. Unfortunately, HIV evolves so rapidly within a single individual that it evades the antibody responses that would protect new cells from infection (see the illustration on page 17). This cycle of antibody production and HIV escape occurs repeatedly over the course of an infection. In addition, HIV can also be passed directly from infected to uninfected T-helpers, thereby completely bypassing the protective shield of antibodies.

Therefore, controlling HIV infection requires eliminating the infected T-helper cells. This is the purview of cytotoxic T cells (CTLs), which recognize infected T-helpers by "seeing" small pieces of viral molecules (epitopes) presented by HLA-A, -B, and -C proteins on the infected T-helper's surface.

CTLs kill infected cells in most viral infections, but usually the cells that they kill are expendable—replaced by the cell division of still-healthy cells (for example, cells lining the digestive system). Unfortunately, in the case of HIV infection, the T-helper cells that are killed are crucial to the immune system's regulation, and, therefore, the actions of the CTLs have serious consequences. Ultimately, the combination of HIV-induced and CTL-induced cell death is not compensated by the production of new T-helpers, and over a period of years, this imbalance reduces the number of T-helpers enough to compromise the immune system's ability to respond to other infections. At this point, symptoms of AIDS ensue, with patients commonly succumbing to the secondary infections; hence, the viral nomenclature—human *immunodeficiency* virus.



A silhouette of the AIDS virus (arrow) is shown adjacent to a portion of a T-helper cell's surface to indicate approximate scale. Protrusions on the T-helper's surface are membrane-associated proteins, one variety of which (known as CD-4) represents the binding site for HIV before its internalization, the first step in its infection of the cell.



Simplified illustration of a cytotoxic T cell (upper right) identifying an HIV-infected T-helper cell (lower left). When a T-helper cell has been infected by the AIDS virus, small pieces of viral molecules, called epitopes (blue), become bonded to the HLA proteins and then transported to the infected cell's surface. After recognizing an HLA/viral-epitope combination with a receptor of complementary shape, the cytotoxic T cell will kill the infected helper. HLA proteins are thus indispensable in the process by which HIV-infected cells are identified and killed. Although only one viral epitope is recognized by a given cytotoxic-T-cell receptor, an individual's immune system potentially responds to dozens of different epitopes; in addition, different epitopes will be recognized by the immune systems of different individuals.

Specifically, the cytotoxic T cells of our immune system recognize these HLA proteins as molecular billboards, advertising that other body cells are virus-infected and should be killed.

Using a combination of viral molecular fragments and the HLA Class-I proteins, cytotoxic T cells can detect and attack HIV-infected T-helper cells, killing cells that normally support the immune system. For several years, biologists have observed that individuals with certain HLA variants progress more slowly to the point when symptoms of AIDS manifest (usually when their T-helper blood count falls below 200 cells per milliliter). But the significance of these observations remained uncertain until clarified by Korber's recent work.

HLA Supertypes

This work was done in the context of a decade-long study of HIV-infected gay men, known as Chicago's Multi-center AIDS Cohort. Korber and her Los Alamos colleagues teamed with researchers from Northwestern and Duke Universities and the Oakland Children's Hospital to investigate the association between HLA types and two measures of the progression from initial HIV infection to the symptoms of AIDS.

To facilitate this analysis, the team grouped the many different HLA types into a smaller sets of "supertypes," where each supertype comprised functionally similar HLA proteins. Each supertype can be thought of as defining the specific HIV molecular fragments to which the immune system will respond. Individuals with different supertypes "see" the virus differently (in an immunological sense).

The team found statistically significant evidence that certain HLA supertypes could be associated with two benchmarks of AIDS progression. The first benchmark was viral load—the amount of virus contained within a unit of an infected individual's blood; the second was the rate of T-helper-cell decline—the rapidity with which these immunologically crucial cells are killed. In the first case, the researchers were able to parse the test population into high, medium, and low viral-load categories that were correlated with specific HLA supertypes; logically, the higher the viral load, the higher the probability of rapid progression to full-blown AIDS.

By ascertaining an infected individual's HLA supertype, the researchers were able to reliably predict that individual's viral load. And more important, those with a low viral load—predictive of slow progression—were also those with the HLA supertypes that occur most rarely in the population at large. For example, supertypes occurring in only 1 to 2 percent of the population tend to have the lowest viral loads; conversely, those occurring in 20 percent or more have the highest.

Advantage of Genetic Rarity

These findings can be extended to the problem of viral escape mutants—genetically altered viruses in each infected person that have avoided recognition and elimination by the immune system. In this context, the researchers posit what is known as a "rare-allele advantage," referring to the low viral-load advantage of rare HLA supertypes. In essence, HIV escape mutants that have evolved in the context of a common HLA-supertype immune system will more likely be effectively combated by the immune system of a newly infected individual who possesses a rare HLA supertype. The rare-supertype immune system can see HIV molecular nuances different from what the common-supertype immune system sees and, therefore, can recognize and better control viruses that have already escaped immune responses of more-common HLA-supertype individuals (see the sidebar on page 18).

The rare-allele advantage is relevant because simply on the basis of population frequency, rare-supertype individuals will, in fact, most likely be infected by sexual partners with one of the more-common HLA supertypes. Overall, this means that individuals with rare HLA supertypes should progress more slowly after infection. Their ability to combat the viral escape mutants of their common-supertype

Conceptual illustration of how an immune system response against one mutant of the AIDS virus is not necessarily effective against other HIV mutants. An antibody (top) binds to the surface glycoprotein (gp120) of an HIV mutant (middle), much as a socket wrench fits a bolt head. However, because of slight differences in molecular shape (conformation), this same antibody will fail to bind to the gp120 structure of a different viral mutant (bottom). Both arms of an antibody are identical in conformation, but in this illustration, one arm has been cut away to facilitate viewing of the antibody's binding with gp120.

HIV and Natural Selection

Natural selection—Darwin's theory of evolutionary change—normally operates slowly, over decades, centuries, or millennia. Mutations occur in genes as a consequence of both environmental conditions and slightly error-prone processes that replicate DNA. Some of these mutations may be advantageous to an organism's survival and reproduction in the face of local environmental circumstances (the selective force). This genetic advantage results in preferential reproduction of the "fittest," which alters the makeup of the organism's local population, creating an altered or even a new species over time.

In the microbial world, the evolutionary process generally proceeds at a greatly accelerated pace, given the rapidity with which bacteria and viruses reproduce. Hence, in HIV infection, this evolutionary process occurs over the time span of months to years, rapidly altering the makeup of the viral population within a single individual. Viral mutations occur continually, the consequence of a massively error-prone RNA/DNA replication process. These viral mutants differ in the structure of the various proteins that mediate their exact form and function. The local selective environment is represented by the infected person's immune system—individualized by his or her HLA (and other) genetic makeup. It is that makeup that determines the ability of the person's antibodies and cytotoxic T cells to recognize and eliminate viral mutants.

But with HIV infections, so many new forms—so many viral mutants—arise that many cannot be eliminated. In a grim example of natural selection, the immune system "selects" those mutants that escape detection and elimination—favoring the survival of the fittest viral mutants at the expense of their human host. Each infected person thus accumulates a collection of "escape mutants" that differ from those of other infected individuals, an ironic outcome when we consider that the immune system generally protects us from succumbing to viral infections.

The research of Korber and others has supported the view that since an individual's HLA genetic makeup defines the viral mutants that he or she attacks—either vigorously, moderately, or weakly—that HLA supertype is a prime contributor to defining the population of escape mutants found in individuals. These surviving viral mutants are the "fittest" for aggressively infecting individuals with the same HLA supertype. They are less effective at infecting individuals with a different HLA supertype.

partner leads to a lower viral load early in infection. A rough analogy can be found in the realm of computer viruses, where viruses targeted to disrupt code in the more-common Windows operating system are often benign in the less-common Macintosh operating system.

This hypothesis has several crucial implications for further work that must be validated in a population with different overall HLA frequencies. Such a study in a native African population in South Africa—with different HLA frequencies and from a region where HIV infection rates top 30 percent—is already in progress, under the aegis of the National Institutes of Health.

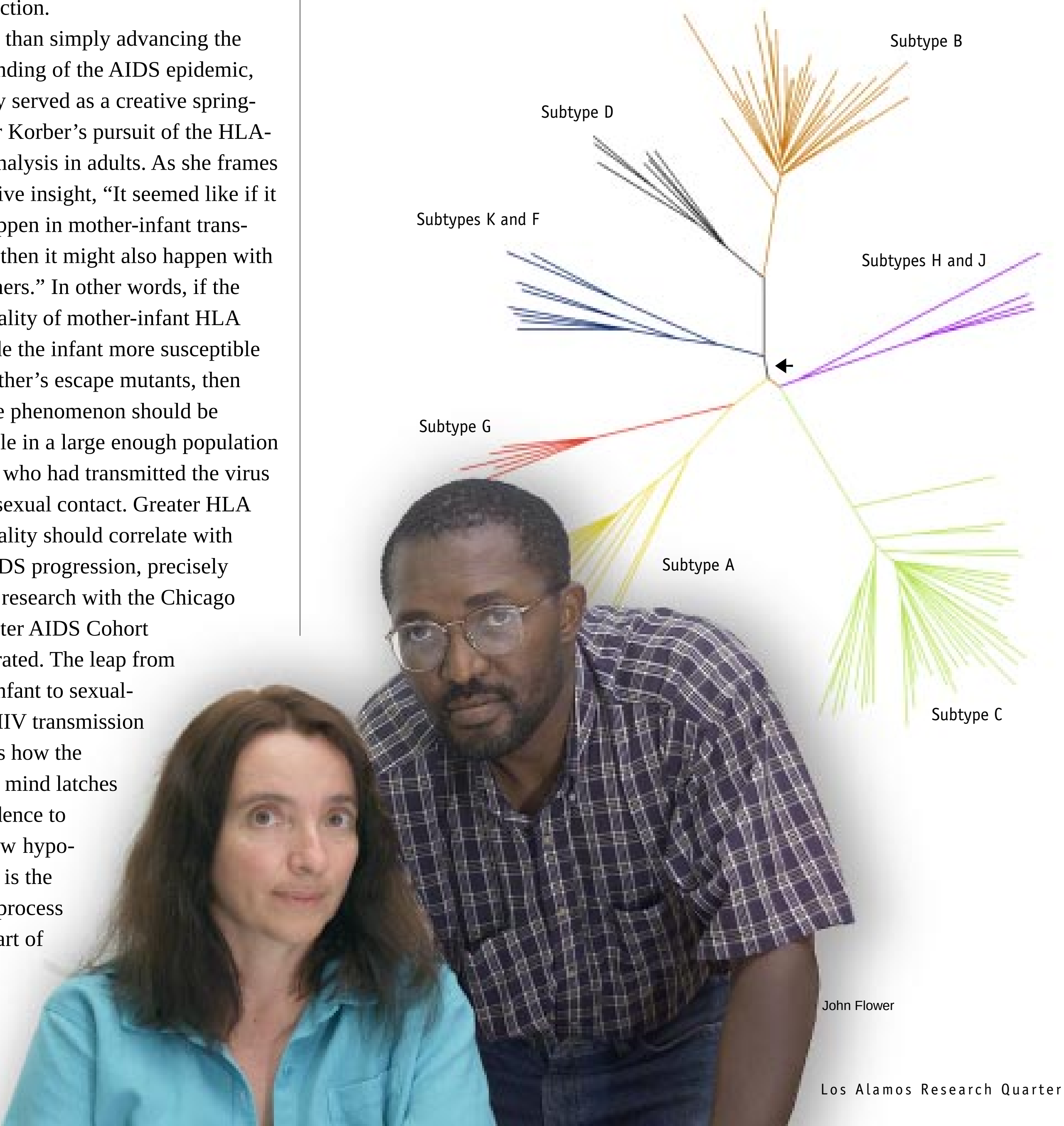
A Creative Leap

The idea to investigate the role of genetic rarity in HIV infection came to Korber from another AIDS study. Researchers and clinicians have long known that the newborns of HIV-infected mothers invariably become infected by their mother's blood and, moreover, that without immediate antiviral drug therapy, these infants progress to AIDS very rapidly. Since a large body of research has pointed to the cytotoxic T cells of the immune system as extremely important in antiviral immunity, the weak cytotoxic-T-cell response in these infants was suspected as contributing to this rapid disease progression. A multiuniversity study—in which Korber participated—of a South African maternity clinic shed some light on this issue.

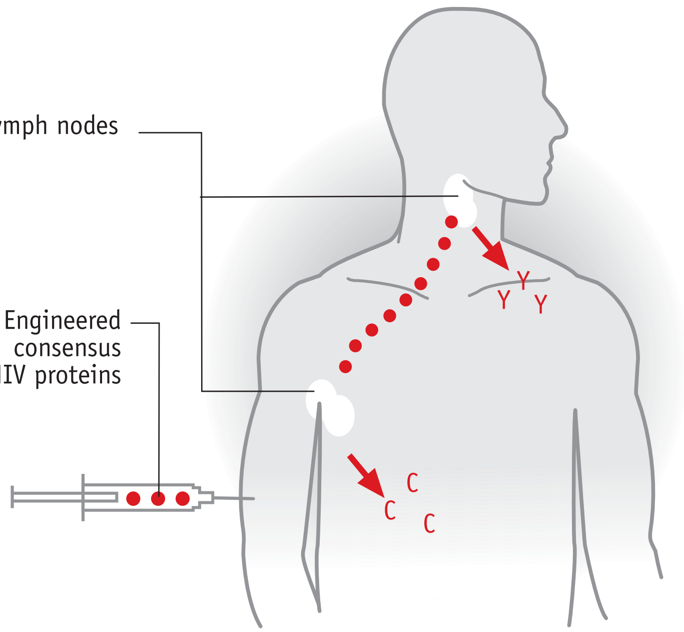
By the laws of inheritance, and ignoring rare chromosomal events, an infant must share half its HLA supertype with its mother. Since that supertype defines the HIV mutants to which the child's immune system responds strongly, weakly, or not at all (i.e., escape mutants), the infected child begins life in a double bind. Armed with an immune system quite similar to its mother's, it also receives, at birth, precisely the viral mutants that have already escaped its mother's immune system. The child thus begins life with an AIDS virus that has already evaded some of the potential immune responses that could otherwise help control the viral infection.

More than simply advancing the understanding of the AIDS epidemic, this study served as a creative springboard for Korber's pursuit of the HLA-related analysis in adults. As she frames her creative insight, "It seemed like if it could happen in mother-infant transmission, then it might also happen with gay partners." In other words, if the commonality of mother-infant HLA type made the infant more susceptible to its mother's escape mutants, then that same phenomenon should be observable in a large enough population of adults who had transmitted the virus through sexual contact. Greater HLA commonality should correlate with faster AIDS progression, precisely what the research with the Chicago Multicenter AIDS Cohort demonstrated. The leap from mother-infant to sexual-partner HIV transmission illustrates how the scientific mind latches onto evidence to create new hypotheses: it is the creative process at the heart of scientific progress.

Bette Korber, postdoctoral research fellow John Mokili, and their Los Alamos colleagues have worked to clarify the evolutionary tree of HIV subtypes and strains. The evolutionary tree shows the genetic relationship among different viral strains, maps the genetic distance between several of the different subtypes of HIV (different colors), and indicates different strains within each subtype. By comparing the genomes (genetic information) of these viruses, Korber and others have been able to reconstruct a genome that would represent a consensus copy (arrow) of this genetic information. This genetic information can then be used to synthesize proteins that can, in turn, become the components of an AIDS vaccine. While at the Lab, Mokili has developed an HIV vaccine database, and he serves as advisor to vaccine developers in his native Democratic Republic of the Congo.



John Flower



To fully protect against HIV infection, a vaccine should contain a viral protein or proteins that can evoke protection against all viral strains—at least in a given locality. In addition, both arms of the immune system must be activated by this engineered consensus vaccine, resulting in the production of antibodies (Y) and cytotoxic T cells (C) capable of attacking the virus when it is transmitted to an uninfected vaccinated individual. Antibodies attack the virus in the blood and other tissue fluids (and by other mechanisms), while cytotoxic T cells attack a virus that has already invaded cells—by killing those infected cells. This infected-cell killing is crucial because even if all detectable virus could be removed from the blood by antibodies (or by drug therapy), the persistence of infected cells would mean that the individual was still actively infected—and viruses would likely reappear in the blood at some later time.

Toward an Effective Vaccine

Among other issues, two considerations are crucial in designing any vaccine: first, stimulating the appropriate part of the immune system and second, including the most-effective molecular components of the target organism. Not surprisingly, Korber's research has implications for both aspects of vaccine design.

Antibody-mediated versus cell-mediated immunity: this quandary has confronted vaccine developers since the 1970s. Originally, the potency of a vaccine was judged by its ability to elicit the production of high concentrations of antibodies in the blood of those immunized. Although this strategy was remarkably effective in protecting against bacterial toxins such as tetanus, immunologists came to appreciate that it was not so effective against certain viruses.

The problem is that viruses spend a portion of their life cycle reproducing inside infected cells, and although antibodies can summon ancillary cell-killing (cytotoxic) mechanisms, these mechanisms may not always be effective at eliminating all infected cells. Even if all virus particles can be removed from the blood by antibodies, the persistence of infected cells means that viruses are still surviving and replicating, that is, that the infection persists. Without stimulating cytotoxic T cells to kill infected cells, the vaccine often cannot eliminate the infection.

For some time, biologists have known that, in the early stages of HIV infection, an initially severe viremia (high blood levels of the virus) attenuates shortly after cytotoxic T cells respond. Although this finding supports the importance of cellular defenses in AIDS, Korber's research linking HLA supertypes to AIDS progression strengthens the significance of that observation for vaccine development, since HLA proteins help cytotoxic T cells recognize and kill HIV-infected cells. This insight has recently been underscored by the failure of the first large-scale AIDS vaccine trial, which used a vaccine designed primarily to elicit antibody rather than cytotoxic-T-cell immunity.

The goal of including the most-effective immune system stimulants in a vaccine is complicated by HIV's viral variability. Recall that within the same HIV genetic subtype—for example, the B subtype found in the United States—the average genetic variation between the viruses found in any two infected individuals is about 15 percent. As a result, a vaccine-stimulated immune response directed specifically against the virus of one person would likely not recognize the virus in the other person—in other words, the vaccine would be useless. By analogy, a socket wrench forged specifically to loosen bolts on one manufacturer's products would not necessarily fit the bolts of another manufacturer that differ in size or shape.

Although this variability is less than the average 30 percent genetic difference between HIV subtypes (such as the U.S. B subtype and the African/Asian C subtype), it is nonetheless a daunting challenge to vaccine developers. To help contend with this viral diversity, Korber and others in the field have designed both consensus and ancestral strains; an ancestral sequence is a model of the historic root (origin) of the epidemic strains. Both of these strategies produce artificial strains that are genetically more similar to modern circulating strains than the strains are to each other. These made-to-order genetic sequences would then be used to synthesize a consensus viral protein or proteins that could be used as the immune system stimulants in a vaccine.

Korber and her colleagues at Duke University have constructed a consensus genetic sequence that is central to all HIV strains found globally and is a model of the most recent common ancestor of HIV-1 strains. In preliminary tests (not involving actual vaccination), they found that antibodies from both B- and C-subtype HIV-infected individuals recognized the consensus viral protein synthesized from this consensus sequence as well or better than they recognized viral proteins from within their own subtype. The implication is that such an engineered protein or group of proteins might ultimately help surmount the problem of extreme viral variation among infected individuals—one of the most challenging obstacles to the development of an effective AIDS vaccine.

Korber is excited about the consensus HIV protein. "So far, it has worked a lot better than I ever thought it would," she notes. "Vaccines are the way to get at preventing the spread of AIDS in the developing world, because [drug] therapy is so inordinately expensive."

Reflecting on a current study in Africa and another planned for China, Korber reasserts her world-health-activist persona: "Can you imagine living in a community and walking down the street where 50 percent of the young men and women are infected? Vaccines are useful in that setting, because it's one, two, three shots, and it's done; and you can afford to do that." There can be no doubt that both HIV-infected individuals and healthcare professionals waging war against the AIDS pandemic sincerely hope that Korber's remarks will prove prophetic. ■

Vaccines are useful . . . because it's one, two, three shots, and it's done; and you can afford to do that.

The Researchers

John Flower

Bette Korber earned a Ph.D. in immunology at the California Institute of Technology. She was a postdoctoral fellow at Harvard University, Los Alamos, and the Santa Fe Institute before joining the Laboratory as a technical staff member in 1993. She serves on the editorial boards of three AIDS and viral research jour-nals, is a member of the AIDS Vaccine Research Working Group, and has helped organize several meetings on HIV and microbial biology. She is also an adjunct faculty member at the Santa Fe Institute and the University of New Mexico Medical School.

Other Los Alamos researchers who contribute to this research include Thomas Leitner, Carla Kuiken, Brian Foley, Brian Gaschen, James Szinger, John Mokili, Robert Funkhouser, Karina Yusim, Dorothy Lang, Kristina Kommander, Ming Zhang, and Una Smith.

RAPTOR Science

Capturing Cosmological “Winks”

by Brian Fishbine

A small robotic observatory system, called RAPTOR, is poised to take movies of fleeting astrophysical events. These movies will help astronomers better understand planetary systems, stars, galaxies, and the universe. Some of RAPTOR’s data analysis techniques can also be applied to defense problems.

Researchers Katherine McGowan and James Wren inside RAPTOR-A, one of four robotic observatories in the RAPTOR system. The wide- and narrow-field telescopes mounted on the platform above them can be aimed at any point in the sky in less than 3 seconds. When RAPTOR’s computers detect a transient optical event in a wide-field image, they aim the narrow-field telescope at the event to take a close-up movie of it.

On January 23, 1999, a NASA satellite detected a brilliant burst of gamma rays 10 billion light years from Earth. The satellite transmitted the burst’s position to a small robotic observatory at Los Alamos National Laboratory called ROTSE, for Robotic Optical Transient Search Experiment. Within 10 seconds, ROTSE pointed its telescopes at the burst and began taking a movie of the most luminous celestial object ever observed. This was also the first time the light from a gamma-ray burst had been recorded as the burst emitted gamma rays. The pulse of light lasted about 80 seconds.

Many distant astrophysical events also produce pulses of light, including exploding stars, extrasolar planets, stellar flares, binary star systems, pulsating stars, and gravitational microlensing events. These “transient optical events” provide important information about the universe. For example, gravitational microlensing studies can help determine the composition of “dark matter,” which makes up 96 percent of the universe’s mass but emits no light and is therefore invisible. Dark matter in the early universe provided the clumps of mass needed to form galaxies, stars, and planets. (Gravitational microlensing

John Flower

John Flower

The three RAPTOR observatories in the mountains just west of Los Alamos (left to right, RAPTOR-P, -A, and -S). The fourth observatory, RAPTOR-B, is at Los Alamos National Laboratory, 38 miles away. RAPTOR-A and -B are identical; together they provide RAPTOR's stereovision. RAPTOR-S measures the color of a transient optical event. RAPTOR-P searches for planets orbiting other stars and catalogs known celestial objects to help identify transient optical events. The observatories' clamshell lids protect the telescope lenses and other hardware from the elements. The lid for RAPTOR-A is shown open. Weather stations on the observatories provide weather data to the control computers.

occurs when the gravity of a dark massive object passing between Earth and a star focuses the star's light to make it brighter as seen from Earth. Microlensing objects include brown dwarf stars and black holes.)

To capture a transient optical event, however, a telescope must center the event in its field of view before the event disappears. The massive telescopes of conventional observatories move too slowly, but small, computer-controlled telescopes are nimble enough for the task.

Last fall, a new system of robotic observatories became operational at Los Alamos. Called RAPTOR, for Rapid Telescopes for Optical Response, the system took its first movie of a gamma-ray burst in response to a satellite alert on December 11, 2002.

However, RAPTOR can do more than respond to satellite alerts. Equipped with sophisticated computer intelligence, it is the first robotic observatory system that can find and study transient optical events on its own. It is also the only robotic observatory system with stereovision, which allows it to discern between transient optical events and nearby space junk, as well as to detect "killer" asteroids (see the sidebar on page 8).

A New Window on the Universe

RAPTOR could also be the first observatory to take movies of such exotic objects as giant flares on sunlike (solar) stars and orphan gamma-ray bursts. Although these objects are thought to exist, they have been difficult to observe: the few sightings of giant solar flares are in doubt, and orphan bursts have not yet been seen. Only RAPTOR has the intelligence and speed to identify and capture these fleeting events.

And there are good reasons to study such events. A giant flare on the sun could destroy Earth's climate and its inhabitants. Even an ordinary "small" flare can affect the weather, overload power grids, and knock out satellites. Studies of giant flares on other solar stars could help astronomers predict the likelihood of such a flare on our sun.

Orphan gamma-ray bursts are of interest because at least some gamma-ray bursts are caused by exploding stars, which seed the universe with the heavy elements of which planets—and people—are made. Studies of gamma-ray bursts will elucidate how stars explode (see the sidebar on gamma-ray bursts on page 10).

System Overview

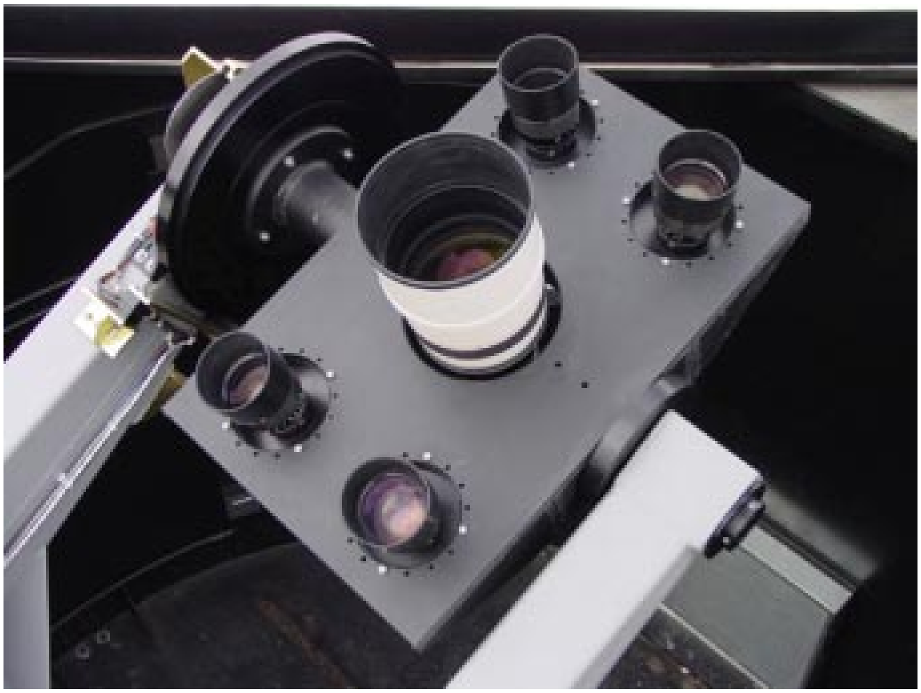
RAPTOR was built by a Los Alamos team headed by astrophysicist Tom Vestrand; the project was funded by the Los Alamos Laboratory Directed Research and Development Program. The system consists of four small robotic observatories. RAPTOR-A, -S, and -P are at Fenton Hill, in the Jemez Mountains west of Los Alamos. RAPTOR-B is at the Los Alamos Neutron Science Center, 38 miles away. Computers located between the two sites analyze data from the observatories and send commands to computers at the sites that control the observatories' telescopes and digital cameras. The computers communicate through the Internet.

RAPTOR-A and -B are identical and together provide RAPTOR's stereovision. Each observatory consists of a wide-field telescope and a narrow-field telescope mounted on a platform that can swivel to any point in the sky in less than 3 seconds. The telescope platform is the fastest ever built.

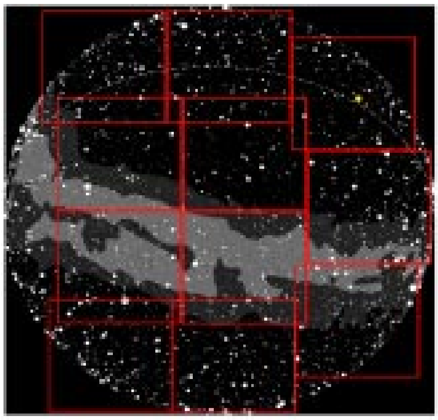
With a field of view of 38 by 38 degrees, each wide-field telescope can cover the sky in eleven patches. However, RAPTOR usually focuses on about four patches near the zenith, where it is easier to measure the brightnesses of celestial objects. Several factors complicate measurements near the horizon: the sky background is brighter because of the sun and nearby towns, celestial objects are dimmer because their light passes through more air to reach the telescopes, and the amount of air the light passes through changes rapidly with the elevation angle.

Usually, RAPTOR monitors one patch of sky for several hours and then moves to another patch. While monitoring, RAPTOR takes two consecutive 30-second exposures through its A and B wide-field

The four 85-millimeter telephoto lenses that make up RAPTOR-A's wide-field telescope surround the 400-millimeter telephoto lens of its central narrow-field telescope.



Tom Vestrand



The patches of sky that the wide-field telescopes usually cover during RAPTOR's nightly searches for transient optical events.

telescopes and analyzes the resulting digital images. If it sees an interesting event, RAPTOR zooms in for a closer look with the two narrow-field telescopes. The system also trains RAPTOR-S on the event to measure how the light intensity changes with wavelength. (RAPTOR-P, a very recent addition, looks for the slight dip in light intensity that can be seen from Earth when an extrasolar planet crosses its parent star's bright disk. This effect was used by a group at Princeton University to discover an extrasolar planet in 2001. RAPTOR-P also catalogs known celestial objects to help the system identify transient optical events.)

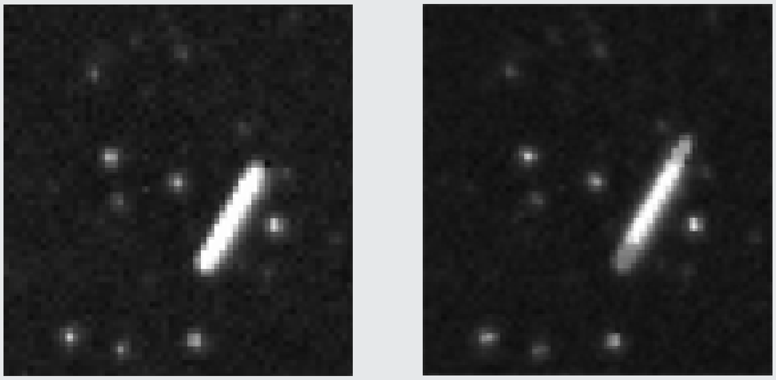
RAPTOR mimics human vision in its searches. If its computer brain detects something interesting in its wide-field "peripheral" vision, it quickly swivels its "eyes" to focus on the action. Then, like the cones in the fovea of the human eye, densely packed light sensors in RAPTOR's narrow-field central vision sharply image the region of interest. RAPTOR also uses two "eyes" for its stereovision.

Detecting "Killer" Asteroids

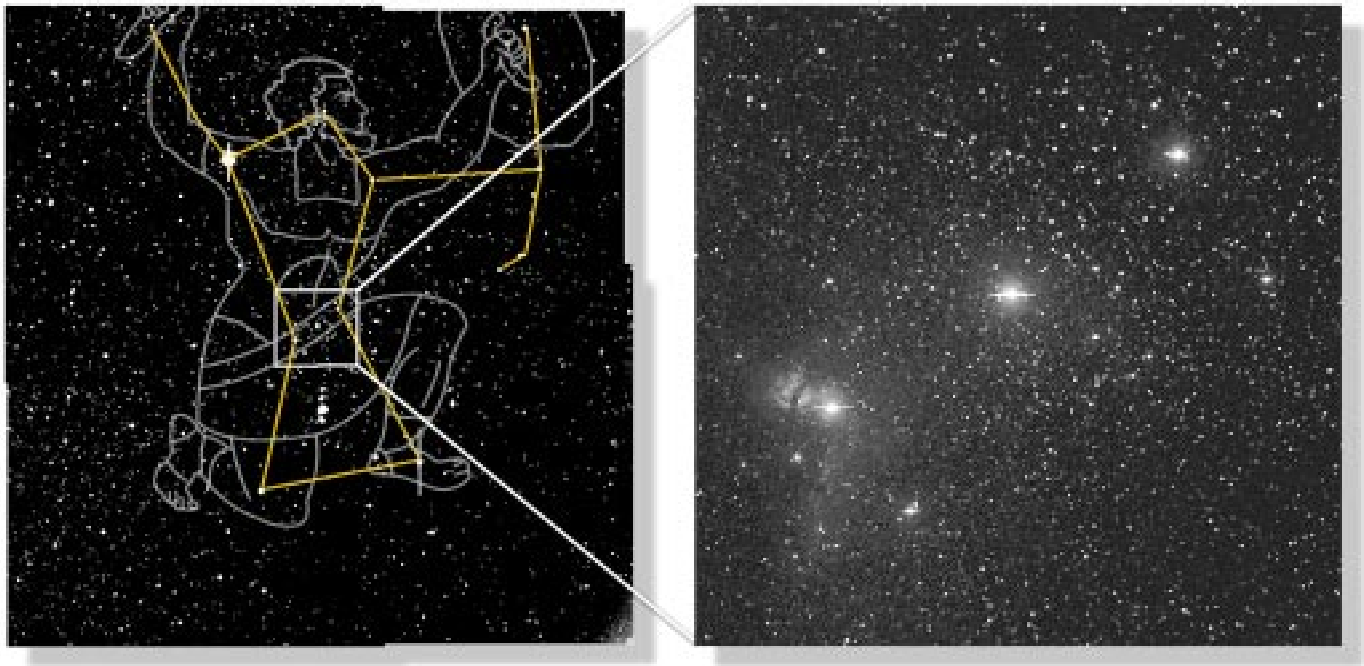
In addition to being able to find transient optical events, RAPTOR can detect "killer" asteroids, like the one that probably wiped out the dinosaurs 65 million years ago. RAPTOR's stereovision permits parallax measurements that can detect such asteroids as far away as the moon. Measuring an asteroid's parallax has an advantage over the current detection method, which looks for the streak an asteroid leaves in a time exposure of the night sky. An asteroid that leaves a streak has a component of motion perpendicular to a straight line drawn from Earth to the asteroid. But the asteroids of most concern are headed straight for Earth and thus leave no streaks. Fortunately, a parallax measurement can easily detect such objects.

Early last year, astronomers calculated that an asteroid would come within 100,000 kilometers of Earth later in the year. Using information provided by the astronomers, RAPTOR took the first-ever stereo views of an asteroid (see photos below). The asteroid's parallax is obvious, as is its streak—which proved the asteroid would miss Earth.

Although a killer asteroid detected as far away as the moon would strike Earth in 8 hours, such advanced warning would give some time to start evacuating people from the coasts, where the impact-induced tsunami would pose the greatest threat to populated areas. (Since three-fourths of Earth's surface is covered by ocean, an ocean impact is the most likely scenario.) Replacing RAPTOR's current telescopes with an array of 1-meter telescopes, however, would enable RAPTOR to provide advanced warning of a week or more.



RAPTOR's stereo view of last year's near-Earth "killer" asteroid.



At each of the RAPTOR-A and -B observatories, four 85-millimeter telephoto lenses provide four digital images that are stitched together to form a 38- by 38-degree wide-field image. On the left is a RAPTOR-A wide-field image of the Orion constellation. At the upper left, the reference star marked by a vertical line is Betelgeuse. The reference star at the lower right (in Orion's foot) is Rigel. To search for a transient optical event, RAPTOR's computers measure the positions and brightnesses of up to 250,000 objects in each wide-field image and compare their positions and brightnesses to those of known celestial objects—all in 10 seconds or less. If the computers find an object that appears to be a transient optical event, RAPTOR zooms in with its narrow-field lenses to take movies of the object. On the right is a 4- by 4-degree narrow-field image taken by RAPTOR-A's 400-millimeter telephoto lens. The three brightest reference stars marked by horizontal lines are the main stars in Orion's belt.

Sky Monitoring

Weather permitting, RAPTOR-A and -B measure the positions and brightnesses of several million stars each night. On a moonless night, their wide-field telescopes can detect objects as faint as the 13th magnitude. (By comparison, the faintest objects visible to the unaided eye—6th magnitude—are 300 times brighter.) Each narrow-field telescope has a field of view of 4 by 4 degrees and can detect objects as faint as the 17th magnitude.

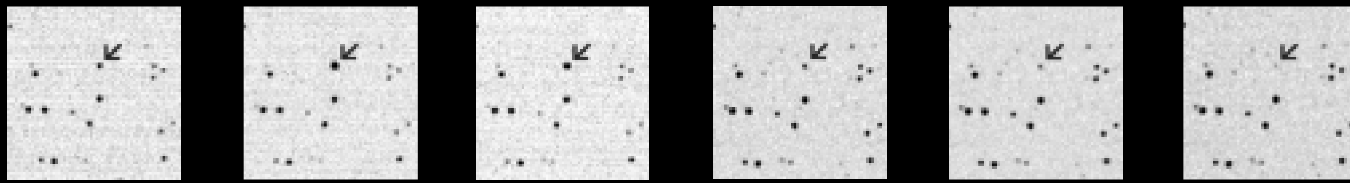
Although RAPTOR is expected to find many transient optical events on its own or by responding to satellite alerts, the data collected through sky monitoring are valuable on their own. For example, by examining the data archives produced during ROTSE's sky monitoring, scientists were able to study the visible light accompanying a brief x-ray event months after a satellite detected it.

To Zoom or Not to Zoom?

To capture a transient optical event, RAPTOR must "think" and act fast. The system has one minute to decide if any one of up to 250,000 objects in a wide-field image is a transient optical event. In contrast, other robotic observatory systems capture transient optical events by chance or by responding to satellite alerts or to commands from humans, who are much slower and less precise than RAPTOR.

To detect a new object in a wide-field image, RAPTOR compares the position and brightness of each object in the image with those of known objects identified in previous scans. (Maintaining the list of known objects is itself a considerable computer task.) To make comparisons, RAPTOR first corrects for changes in the objects' apparent positions caused by optical aberrations in the telescope lenses and for changes in the objects' apparent brightnesses caused by atmospheric attenuation and lens vignetting (the loss of light near the edge of a lens). RAPTOR makes these corrections for all the objects in a wide-field image in 10 seconds or less.

When RAPTOR finds a new object in the first of the two consecutive images provided by both its A and B observatories, it determines if the object



22 s M=11.7 | 47 s M=8.9 | 73 s M=10.0 | 281 s M=13.1 | 447 s M=13.8 | 612 s M=14.3

Mysterious Gamma-Ray Bursts

Gamma-ray bursts were discovered in signals from satellites designed and built at Los Alamos. The satellites' mission was to verify compliance with the nuclear test ban treaty by looking for the x-rays and gamma rays produced by a nuclear explosion in space. Los Alamos scientists published their discovery of gamma-ray bursts in 1973, concluding that the sources of the bursts were cosmic and not terrestrial or solar. The scientists also tried—but failed—to relate the bursts to supernovas.

Burst gamma rays are photons with energies of ten thousand to several million electronvolts. Because of their energies, these gamma rays are highly attenuated by the atmosphere and thus can be detected only in space. (In contrast, the photons of light emitted by some bursts have energies of about 1 electronvolt and pass easily through the atmosphere. These photons can be detected by ground-based instruments such as the RAPTOR observatories.)

Modern satellites detect about one gamma-ray burst a day. A burst can last from a few thousandths of a second to more than 15 minutes. The closest burst, detected on March 29, 2003, was 2 billion light years from Earth, but 10 billion light years is more typical. Such large distances mean the bursts have occurred at the "edge" of the universe, or when it was much younger. For example, the light from a burst 10 billion light years away—which has taken 10 billion years to reach Earth—occurred when the universe was 30 percent of its present age. Gamma-ray bursts thus provide a window on the early universe.

For a time, the bursts' enormous energies puzzled astrophysicists. For example, the gamma-ray burst captured on January 23, 1999, by ROTSE, a robotic predecessor of RAPTOR, was the most luminous celestial object ever observed. (Although the observed brightness of an object decreases as its distance from the observer increases, its *intrinsic* brightness, or luminosity, is independent of the distance.) Assuming the burst emitted radiation uniformly in all directions, astrophysicists estimated its energy to be about 10^{32} megatons, or the energy of two solar masses. (Einstein's equation, $E = mc^2$, equates energy E and mass m, where c is the speed of light.)

However, light measurements of the 1999 burst made more than three days after it occurred supported the idea that the gamma rays and the light were in fact emitted in collinear beams that just happened to shine on Earth, like a searchlight. For a beam scenario, the estimated burst energy was more reasonable—about 10^{29} megatons, the energy of a typical supernova explosion.

Astrophysicists now believe that a burst's gamma rays are emitted in a tight beam and that its light is emitted more broadly. Thus, if Earth is slightly off the beams' axis, the light flash would be seen on Earth but the gamma-ray burst would not. Such bursts are called orphan gamma-ray bursts. Although orphan bursts have never been observed, astronomers believe they exist, and RAPTOR is expected to find many of them. When it does, astronomers will be able to compare the rates at which orphan bursts and ordinary bursts occur to determine the average width of the gamma-ray beam. This information will shed light on how the bursts are produced.

ROTSE measurements also showed that the light from the 1999 burst faded rapidly in the first 10 minutes, as shown above in the six-frame movie. (These first-ever measurements of a burst's early light were possible only because ROTSE's telescopes were pointed at the event within seconds of the satellite alert.) The magnitude data cast doubt on a generally accepted theory that the shock wave generated by a supernova interacts with the gas surrounding the explosion to produce both light and gamma rays. Instead, the ROTSE data suggested that the gamma rays are produced closer to the explosion.

Although there had long been hints that gamma-ray bursts and supernovas were connected, there had been no proof of that connection until the "nearby" burst of March 29, 2003. Because the burst was so close and bright (astronomers joked about it casting shadows), scientists were able to measure its light in detail for several weeks. About a week after the burst, the spectral signature of a supernova appeared in the burst's fading afterglow, which proved that gamma-ray bursts and supernovas can be intimately connected. In fact, it is now clear that at least some gamma-ray bursts are produced by supernovas.

appears in the second images as well. This procedure eliminates artifacts produced, for example, by a cosmic ray passing through a light-sensor element in one of the digital cameras. False positives are a major problem for robotic observatories.

If an object passes this first test, RAPTOR measures the object's parallax to determine if the object is truly distant or merely an airplane, a meteor, a satellite, or a piece of space junk orbiting Earth. To qualify as a transient optical event, the object must be at least as far away as the moon.

RAPTOR measures parallax by comparing the two images from its A and B observatories. The positions of distant objects are the same in the two images, but the positions of close objects are different. This difference is the parallax. As with human vision, the closer the object, the greater the parallax. Stereo comparison also identifies malfunctioning light-sensor elements in the digital cameras, which can also mimic transient optical events.

No Shortage of Brains

To perform its complex tasks quickly, RAPTOR uses sophisticated software residing on nearly twenty personal and server computers. RAPTOR has far more computer intelligence than any other robotic observatory system.

Each telescope platform is controlled by its own personal computer. Also, a dedicated computer transfers the images from each digital camera to the system, which takes about 5 seconds per image. Because a computer is assigned to each camera, the transfers occur in parallel to reduce the total image-transfer time. For example, the total transfer time for a wide-field image, which consists of four slightly overlapping smaller images stitched together, is also about 5 seconds. The computers assigned to the cameras also measure the celestial objects' positions and brightnesses.

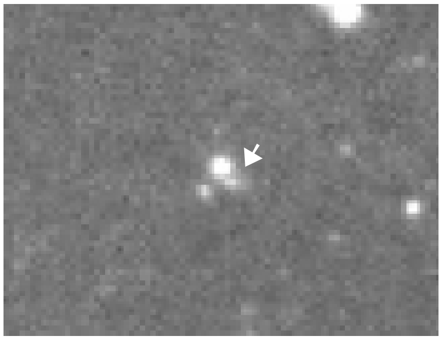
An image-server computer at each site analyzes data from the site's digital cameras and their computers for possible transient optical events. The image server then sends a list of candidate events to an alert-server computer located between the two sites. The alert server compares the lists from RAPTOR-A and -B observatories and identifies new objects that have no measurable parallax.

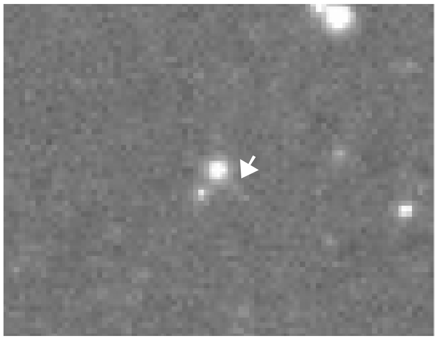
RAPTOR's master control consists of three computer programs that control the computers that in turn control the telescope platforms and the digital cameras. On the basis of data it receives from weather stations at each site, one of these programs also controls the observatories' domes. The programs also reside on a computer located between the two observatory sites.

Finding a Needle in a Haystack

RAPTOR's sky-monitoring data archives will provide valuable information. They offer a nearly continuous record of the light emitted by a large fraction of the celestial objects visible from Earth with a brightness of at least the 13th magnitude. Each week, sky monitoring adds up to 1 terabyte (1,000 gigabytes) to the data archives, which can be mined for interesting astronomical objects.

For example, a team of scientists from Los Alamos and the University of





RAPTOR captured its first transient optical event on December 11, 2002. The upper photo shows the light emitted by a gamma-ray burst 64.9 seconds after a satellite detected the burst. In the lower photo, taken 9 minutes after the burst was detected, the object is nearly invisible. These images were taken by RAPTOR-B. (RAPTOR-A was not yet operational.) They proved that even a gamma-ray burst with weak gamma-ray emission (as measured by the satellite that detected the burst) can generate a bright burst of light.

The first of thirty frames in a movie of the 1999 Leonid meteor shower taken by ROTSE, a robotic predecessor of RAPTOR. This frame shows the cloud produced when a meteor exploded at an altitude of about 85 kilometers just northwest of Las Vegas, New Mexico.

Michigan has used a computer program to identify 1,781 variable stars in the ROTSE data archives. (Variable stars help astronomers measure distances to other galaxies and study the galaxies' evolution.) About 90 percent of the variable stars had not been identified before. The computer program found the variable stars using the same process human astronomers follow. However, a team headed by Los Alamos astrophysicist Przemyslaw Wozniak has also programmed a computer to devise its own ways to find patterns in the ROTSE data. This method could discover entirely new types of stars.

Wozniak's "machine-learning" technique resembles those used by credit card companies to detect fraud from anomalous spending patterns. (In fact, Los Alamos scientists developed some of the machine-learning techniques currently used by MasterCard to detect fraud.) In both cases, the techniques look for a few interesting patterns or events hidden in huge masses of data. In essence, they are looking for a needle in a haystack.

Defense scientists are also interested in finding "needles." They want to distinguish between the warheads and the decoys deployed by a hostile intercontinental ballistic missile, a scenario that includes many fast-moving objects with varying light intensities against a backdrop of stars. Defense scientists also want to detect the unique electromagnetic signature of a missile launch within a "forest" of signals whose sources range from cell phones to the sun. The techniques developed to help RAPTOR find needles in the cosmic haystack could help solve these problems as well. ■

The Researcher

John Flower

Tom Vestrand has a Ph.D. in astrophysics from the University of Maryland. His primary interests are high-energy astrophysics and the physics of rapid astrophysical transients. Before joining Los Alamos in 1999, he was a faculty member at the University of New Hampshire for 10 years and the principal investigator for the Gamma-Ray Spectrometer Experiment on NASA's Solar Maximum Mission Satellite. He was also involved in several other spacecraft missions.

Nuclear Renaissance

Reevaluating Nuclear Power's Future

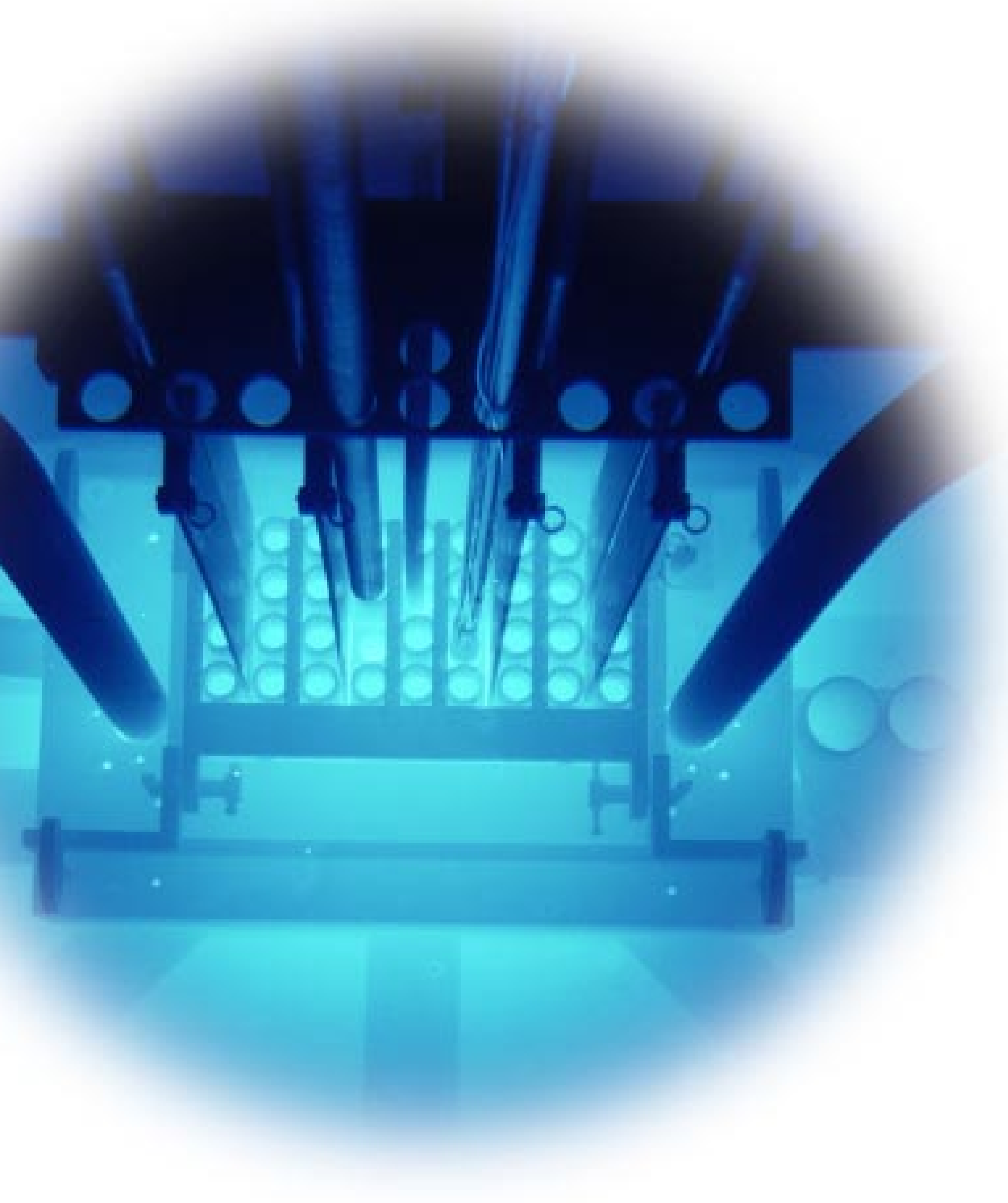
by Brian Fishbine

Growing levels of atmospheric carbon dioxide are raising concerns of global warming and sparking renewed interest in nuclear power. Unlike coal- and gas-fired power plants, nuclear power plants provide electricity without emitting carbon dioxide. They could also enable a hydrogen economy.

The core of the Omega West Reactor, which was used at Los Alamos from 1956 until 1992 for a variety of research projects. The reactor's fuel rods were immersed in water, which provided cooling, moderation, and radiation shielding. The blue glow—called Cherenkov radiation—is light emitted by electrons from the reactor that travel faster than the speed of light in water.

Eighty-five percent of the 14 million megawatts of power consumed worldwide comes from burning fossil fuels, a process that annually pours 27 billion tons of carbon dioxide, a major greenhouse gas, into the atmosphere. We can minimize carbon dioxide emissions by producing and using energy more efficiently; by sequestering carbon dioxide; by expanding the use of renewable energy sources, such as solar energy, wind power, and hydroelectric power; and by expanding the use of nuclear power, which is the only large-scale source of electricity other than hydroelectric power that does not generate greenhouse gases.

In fact, nuclear power plants already provide 20 percent of the electricity consumed in the United States. There are currently 104 nuclear power plants



in 31 states (see the map on page 24). However, the Department of Energy forecasts that by 2020, the United States will almost double its electrical power consumption to more than 800,000 megawatts. To supply that power will require 1,300 to 1,900 new power plants, many of which could be nuclear.

But to expand the use of nuclear power, we must ensure that existing nuclear power plants continue to operate safely beyond their original design lifetime of 40 years, simplify reactor regulations without compromising reactor safety, and build new nuclear power plants that are simpler, cheaper, safer, and less prone to terrorist attack. In addition, we must dispose of spent nuclear fuel both safely and securely and prevent the diversion of weapons-grade nuclear material from existing power plants. Several Los Alamos programs address these issues.

Reactor Safety, Security, and Economics

Los Alamos scientists first began to work with reactor fuel—specifically, uranium and plutonium—during the Manhattan Project because these elements also fuel nuclear weapons. Since then, Los Alamos studies of uranium and plutonium have contributed to both weapon and reactor science.

One of the more recent reactor-related programs at Los Alamos has improved the safety of existing power reactors. In 1998, at the request of the U.S. Nuclear Regulatory Commission (NRC), Los Alamos scientists began studying a problem with the emergency core-cooling systems of nuclear power plants.

Normally, a nuclear reactor's core is cooled in a bath of water under high pressure; the core and bath are contained in a large vessel. A break or leak in the pipes that circulate water to and from the vessel or in the vessel itself could lead to excessive core heating. The emergency system cools the core if the regular cooling system fails.

The principal investigator for the cooling-system work done at Los Alamos was D. V. Rao, now deputy director of Decision Applications Division. Using computer simulations, small-scale experiments, and prototype tests, the Los Alamos scientists determined the severity of the problem and ways to fix it. They also helped the NRC develop regulations to address the problem and inspected power plants where corrections had been made. So far, thirty-five nuclear power plants have been corrected.

Los Alamos has also recently teamed with Sandia National Laboratories in Albuquerque to study the vulnerabilities of nuclear facilities to terrorist attacks, including the impact of an aircraft. (Nuclear facilities include nuclear power plants, plants that produce reactor fuel or medical isotopes, and the cooling ponds where spent nuclear fuel is stored.) The team is also developing ways to protect existing and future facilities from such attacks.

Over the last 30 years, Los Alamos has supplied most of the systems used by the International Atomic Energy Agency to track enriched, fresh, spent, or reprocessed reactor fuel at nuclear facilities worldwide. This work has

One hundred and four nuclear power plants in thirty-one states provide 20 percent of the electricity used in the United States.

reduced the possibility of nuclear materials being diverted from peaceful uses to make nuclear weapons.

Over the last 20 years, Los Alamos scientists have also used advanced statistical techniques and computer simulations to develop precise estimates of reactor safety under various operating conditions. A major result of this research is the Transient Reactor Analysis Code (TRAC), which simulates all aspects of nuclear power plant operation.

TRAC is currently the only code used by the NRC to obtain estimates of reactor safety under the most likely conditions (as opposed to worst-case estimates, which are ultraconservative). The Naval Reactors organization, which is responsible for the reactors used in U.S. submarines and other naval vessels, also uses TRAC to study reactor safety.

Recently, the NRC has used TRAC estimates to approve eighteen nuclear power plants to operate 20 years beyond their 40-year design life. The NRC has also used TRAC estimates to relax some power plant regulations without compromising plant safety, a measure that reduces plant complexity and cost. Finally, the NRC has used the estimates to authorize some plants to operate at power levels 5 to 10 percent above those specified in their original licenses, reducing the cost of the electricity the plants produce.

Another Los Alamos computer code widely used for reactor studies is MCNP, for Monte Carlo N-Particle (transport). MCNP simulates how neutrons and other forms of radiation move through a reactor's core. (Neutrons produce fission reactions in the reactor's uranium or plutonium fuel, which in turn produce more neutrons to generate a controlled chain reaction.) While TRAC simulates the operation of an entire nuclear power plant, MCNP focuses on the detailed physics in the reactor's core.

MCNP performs its calculations using Los Alamos data on nuclear cross sections, which measure the probabilities of a neutron interacting with the atoms of various elements. Such data are essential for detailed reactor-core calculations. The code and the cross-section data are used worldwide to design reactors, analyze radiation-shielding methods, calculate radiation doses for safety analysis, and design nuclear instruments and detectors.

Los Alamos scientists are also performing experiments to determine how the high levels of radiation in a reactor degrade its metallic structural members and its fuel rods, which consist of uranium or plutonium in ceramic forms. Materials scientist Robert Hanrahan is involved in this research. Understanding how intense radiation affects the materials in a reactor is key to determining reactor lifetime and safety, Hanrahan says.

Some of these experiments are performed at the Los Alamos Neutron Science Center (LANSCE), where neutrons produced by a linear accelerator can be used to simulate the neutron flux in a nuclear reactor. In addition, a collaboration between researchers at the Laboratory and the University of Florida has developed ways to study corrosion in high-radiation environments, the major cause of the deterioration of the materials used in nuclear power systems.

Priming the Nuclear Pump

About a decade ago, Congress asked the NRC to improve the licensing process for nuclear power plants, which had often invited protracted lawsuits by environmental groups. These lawsuits, which could be filed even after the plant had been built and tested, could delay a plant's startup by several years or more. Such delays increased the plant's final cost and discouraged investors, the main reasons that reactors are not being built today.

The NRC's solution, which has been available since 1995, is to license a plant simply by confirming that its components correspond exactly with those in one of three approved plant designs: the Westinghouse AP-1000, the Combustion Engineering System 80+, and the General Electric ABWR. Working with scientists around the nation, the NRC used TRAC and small-scale experiments to determine that these designs are safe.

Codes like TRAC and MCNP will also be useful for designing new nuclear power plants that are simpler, safer, and cheaper than existing plants. The reason, Rao says, is that existing plants were scaled up from reactor designs developed in the 1950s to power submarines. As they were scaled up, the plants became more complicated and therefore more expensive and less reliable. In addition, each plant design was unique, which complicated licensing.

Commercial nuclear power plants could be much simpler and safer, Rao says, by generating the same amount of power in a larger volume of the reactor's core. In such an arrangement, the core could be cooled by natural convective flow of the cooling water rather than forced circulation. Convective cooling uses the fact that hot water naturally rises above cold water, whereas forced circulation uses pumps and valves to circulate the water. According to Rao, most postulated accidents involve either failed pumps or valves or breaks or leaks in the pipes that circulate the water.

Dealing with the Waste

To date, U.S. nuclear power plants have produced 40,000 tons of spent nuclear fuel. The spent fuel consists of 95.6 percent uranium, 3.0 percent stable or short-lived fission products, 0.9 percent plutonium, 0.3 percent cesium and strontium, 0.1 percent minor actinides (neptunium, americium, and curium), and 0.1 percent long-lived fission products in the form of isotopes of iodine and technetium.

The spent fuel's uranium is mostly uranium-238 and contains too little uranium-235 to be considered weapons grade. In fact, spent-fuel uranium is less radioactive than natural uranium ore and can, when separated from the spent fuel, be stored as "low-level" waste. The cesium and strontium, however, are literally quite hot from radioactive decay and require special storage for

Missouri Geographic Alliance

Steam rises from the cooling tower of a nuclear power plant in southern Callaway County, Missouri. The nuclear reactor is the dome-shaped building at right.

about 300 years, after which time they have mostly decayed into harmless elements. The plutonium isotopes and minor actinides remain dangerously radioactive for hundreds of thousands of years. Thus, about 1 percent of the spent fuel—the plutonium, the minor actinides, and the long-lived fission products—currently requires secure, long-term isolation.

The present plan is to store spent fuel rods at the Department of Energy's Yucca Mountain Facility in Nevada, a protected underground repository. But storing fuel rods from the one thousand 1-gigawatt nuclear power plants that could be deployed worldwide by 2050 would require a new repository the size of the Yucca Mountain Facility every three or four years.

Obviously, if there were less long-lived waste, fewer repositories would be needed. In collaboration with other national labs, universities, and industry, Los Alamos scientists are studying ways to separate the waste so that some of it can be recyled in reactors or transformed (transmuted) into short-lived or nonradioactive elements. If successful, this program, called the Advanced Fuel Cycle Initiative, could eliminate the need for a second national repository and reduce the number of global repositories required.

An element can be transmuted or fissioned (split by a nuclear reaction into lighter elements) by exposing it to neutrons. Copious neutrons are produced in reactors or by accelerators such as the one at LANSCE. Fissioning spent-fuel plutonium in a reactor would not only eliminate the need for its long-term storage but would also produce useful energy. Los Alamos has the only facility in the United States where reactor fuels that contain plutonium can be studied and developed.

The Hydrogen Bonus

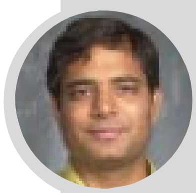
Nuclear reactors could help make a hydrogen economy feasible and further reduce emissions of greenhouse gases as well as our dependence on foreign oil. Burning gasoline in internal combustion engines produces carbon dioxide as well as nitrogen- and sulfur-based gas pollutants. Electric vehicles powered by hydrogen fuel cells produce only water vapor.

In fact, President Bush recently announced a national program to develop hydrogen-powered cars, trucks, homes, and businesses. At present, however, 90 percent of the hydrogen produced industrially is made by "reforming" natural gas. Although reformed hydrogen is economical, reforming produces large amounts of carbon dioxide. But if nuclear power plants could produce electricity more economically, they could produce hydrogen electrolytically by decomposing water into hydrogen and oxygen. Or special high-temperature reactors could thermally decompose water. No carbon dioxide would be produced by either option.

The Department of Energy's Nuclear Hydrogen Initiative calls for building a nuclear reactor to demonstrate the feasibility of generating hydrogen economically by 2015. Los Alamos simulation codes will likely be used to design such a reactor and to show that it is safe. ■

The Researchers

Robert Hanrahan Jr. has a B.S. and M.S. in nuclear engineering and a Ph.D. in materials science from the University of Florida. He joined the Lab as a technical staff member in 1996. His research has focused on materials behavior for nuclear weapon and reactor applications. He has been a technical reviewer for the materials corrosion and aging models used to evaluate the Yucca Mountain Facility.



D. V. Rao has a Ph.D. in nuclear engineering from the University of New Mexico. Since joining Los Alamos, he has directed several NRC-sponsored reactor studies and is currently the Lab's NRC program manager. His research interests include special-purpose nuclear reactors, energy security, nuclear counterproliferation, and risk assessment for homeland security.

Mike O'Keefe and LeRoy N. Sanchez

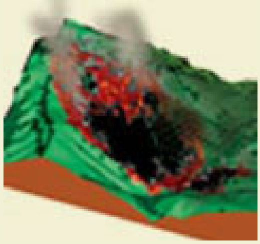
Spotlight
Los Alamos in the News

Lab Wins Eight R&D 100 Awards

In an achievement unequaled since 1988, Los Alamos National Laboratory had eight winners in this year's R&D 100 Award competition, the most of any Department of Energy laboratory in the 2003 contest. The award is a coveted prize, signifying excellence in research and development. R&D Magazine sponsors the annual international competition to honor the previous year's 100 most-significant technological advances—the ones most likely to benefit humanity.

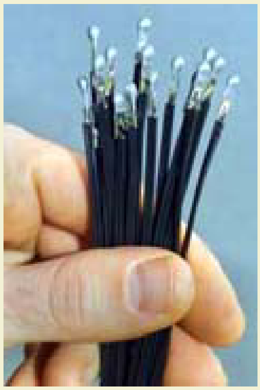
The Lab has participated in the competition since 1978 and has won eighty-nine R&D 100 Awards over those twenty-five years. Those wins are proof that Lab science produces more than warheads. Los Alamos is proud of pursuing science that serves society, and our eight award-winning technologies this year emphasize the breadth of that service.

Two of this year's winners are representative of the Lab's traditional national security focus. BASIS, the Biological Aerosol Sentry and Information System, is sensor technology that stands guard in public places to detect and quickly identify airborne hazardous biological agents. It has already done duty at the 2002 Winter Olympics in Salt Lake City and now is being nationally deployed under the name BioWatch to guard against large-scale urban attacks. CARISS, Compositional Analysis by Raman-Integrated Spark Spectroscopy, integrates both elemental and compositional chemical analysis in a single instrument to detect, even from a distance, hazardous chemical agents or materials used



FIRETEC simulation

Flexible Superconducting Tape



Super-Thermite Electric Matches

in weapons of mass destruction. Useful for identifying elements and compounds in soil, CARISS will also find a place in space exploration, for analyzing the composition of planetary surfaces. Plans are already being made to include it on the next Mars rover.

Los Alamos is known for high-performance computers that can simulate weapons and model global ocean currents, but another of the Lab's R&D 100 winners is a supercomputer for the masses. Green Destiny is a 240-processor system that occupies less than 6 square feet and draws no more than 5.2 kilowatts of power. In addition to being small, Green Destiny is decidedly less temperamental than traditional supercomputers: it runs reliably in facilities with no cooling, humidification, or air filtration—a supercomputer businesses can afford.

The developers of FIRETEC combined computer skill with physics expertise to produce the first physics-based wildfire model. FIRETEC predicts the complex behavior of wildfire by representing, in three dimensions, a fire's constantly changing interaction with its environment (fuels, atmosphere, and topography). In the hands of fire, fuel, and land managers, this technology has the potential to prevent loss of life, property, and natural resources.

The world has a constantly growing appetite for electrical power. Another winning Lab technology— Flexible Superconducting Tape —holds the promise of highly efficient power transmission. The tape carries 200 times the electrical current of copper wire with no resistance and can be wrapped into a tight coil with no loss of superconductivity. Because the tape loses no electricity to resistance, it can reduce the cost of generating and transmitting electrical power. Its ease of production gives it an attractively low processing cost.

Super-Thermite Electric Matches were designed principally for the entertainment industry. Electric matches are used to ignite fireworks remotely. The Lab's newly designed matches are safer because they resist accidental initiation. In addition, they produce no toxic lead smoke, making them perfect for initiating displays at sporting events, holiday celebrations, and music and theatre productions.

A valuable tool for manufacturers, FlashCT is a high-speed scanning system that produces three-dimensional images of the exterior and interior geometries of objects. FlashCT images can be used for quality assurance and design engineering and are particularly well suited to the rapid manufacturing of customized devices. Also for manufacturers, PowerFactoRE , developed through a collaboration with Proctor & Gamble, is a suite of reliability engineering tools that can be used to enhance the performance of manufacturing systems.

The Lab's R&D 100 Awards demonstrate that national defense work can lead to scientific innovations with wide-reaching benefits.

Many R&D 100 winners are already working with outside agencies and companies to move their inventions into the private sector. The partnership with Proctor & Gamble that produced PowerFactoRE was only one such collaboration among this year's winners. BASIS was a huge cooperative enterprise, linking Los Alamos with Lawrence Livermore National Laboratory and a private company—Rupprecht and Patashnick Co., Inc. The developers of the Super-Thermite Electric Matches also collaborated with a private company, PyroLabs, Inc.

CARISS was developed with the University of Hawaii, and FIRETEC developers had important input from the United States Forest Service. FlashCT is the work of both the Laboratory and HYTEC, Inc., a local company that has turned a Lab-developed technology into a successful business. The Flexible Superconducting Tape has already attracted industrial partners committed to commercializing it. All in all, entering the R&D 100 competition is a net gain—offering advanced technology for the marketplace and an opportunity for Laboratory researchers to have a positive impact on society as a whole.

—Eileen Patterson